

# **Unlocking the Mystery of Columbia's Tragic Accident Through Materials Characterization**

**Presented to**

**Mississippi State University Materials Working Group**

**By**

**Dr. Sandeep Shah**

**Gregory Jerman**

**James Coston**

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**Acknowledgement: This work is a result of a team effort  
involving KSC, JSC, MSFC, LaRC, GRC, Boeing, USA  
and Columbia Accident Investigation Board personnel. <sub>1</sub>**



IN MEMORY  
OF STS-107  
ASTRONAUTS





Space Shuttle Columbia In Orbiter Processing Facility (OPF) and Rollout to Vehicle Assembly Building (VAB).

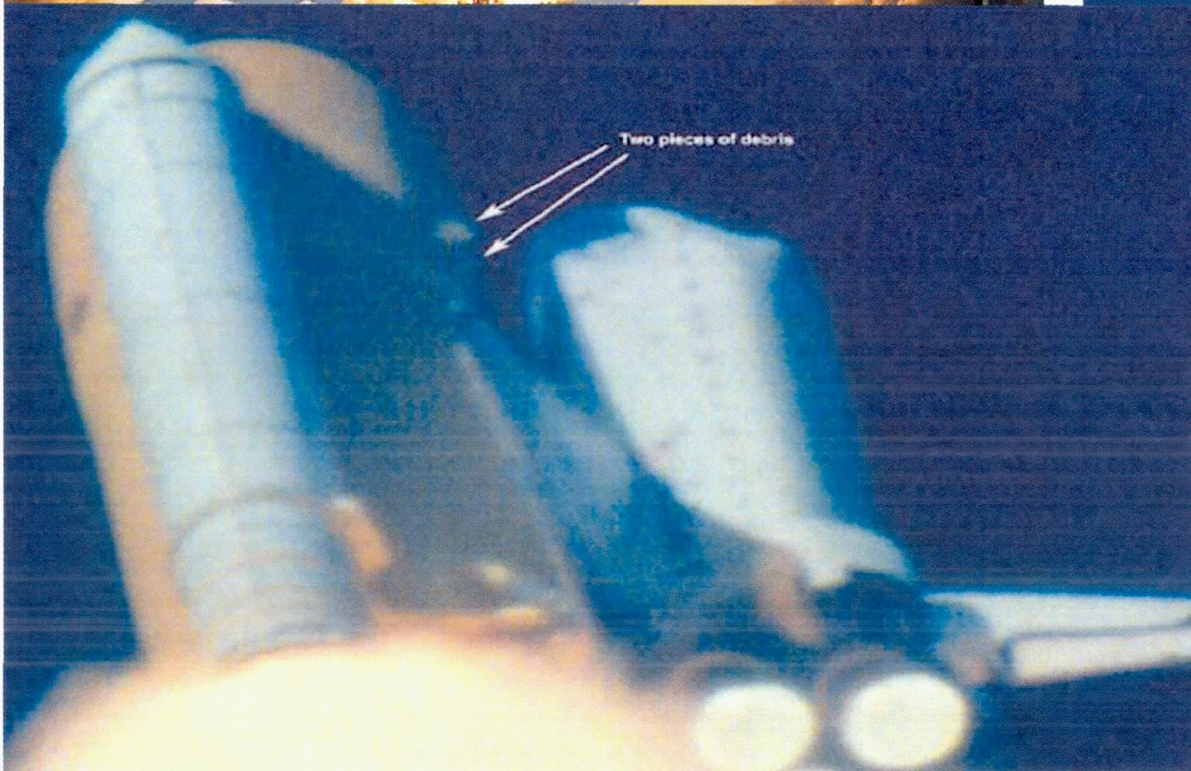
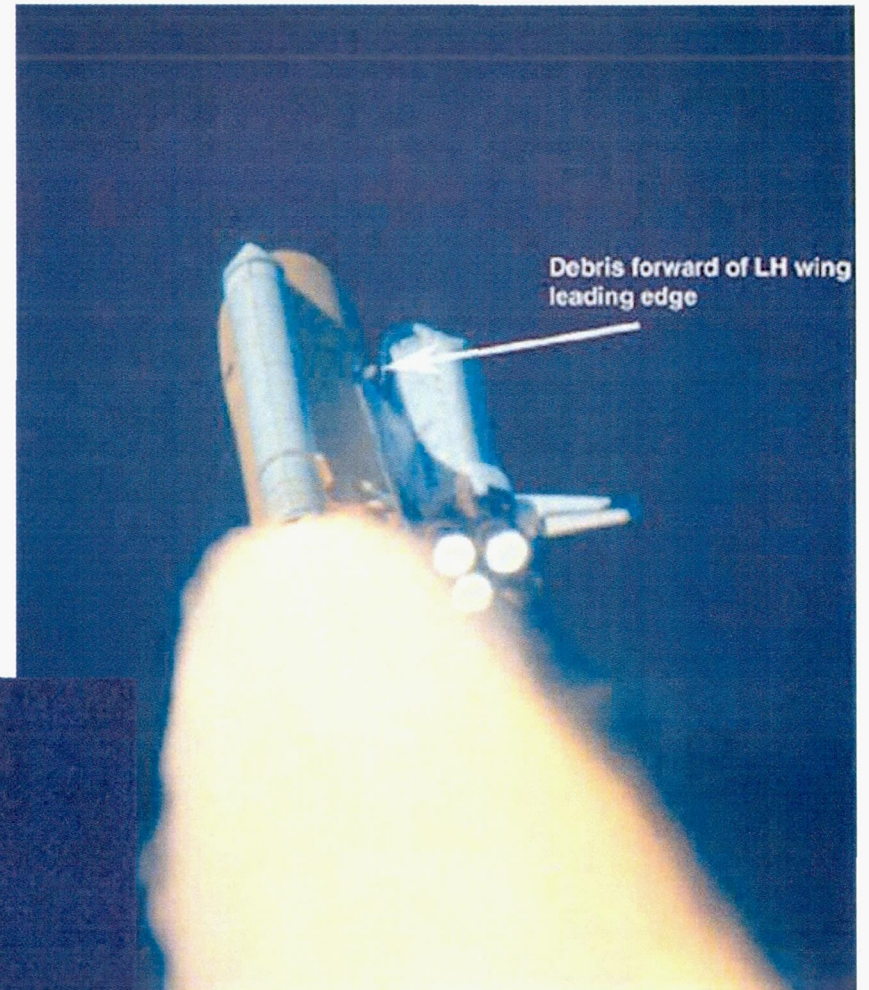
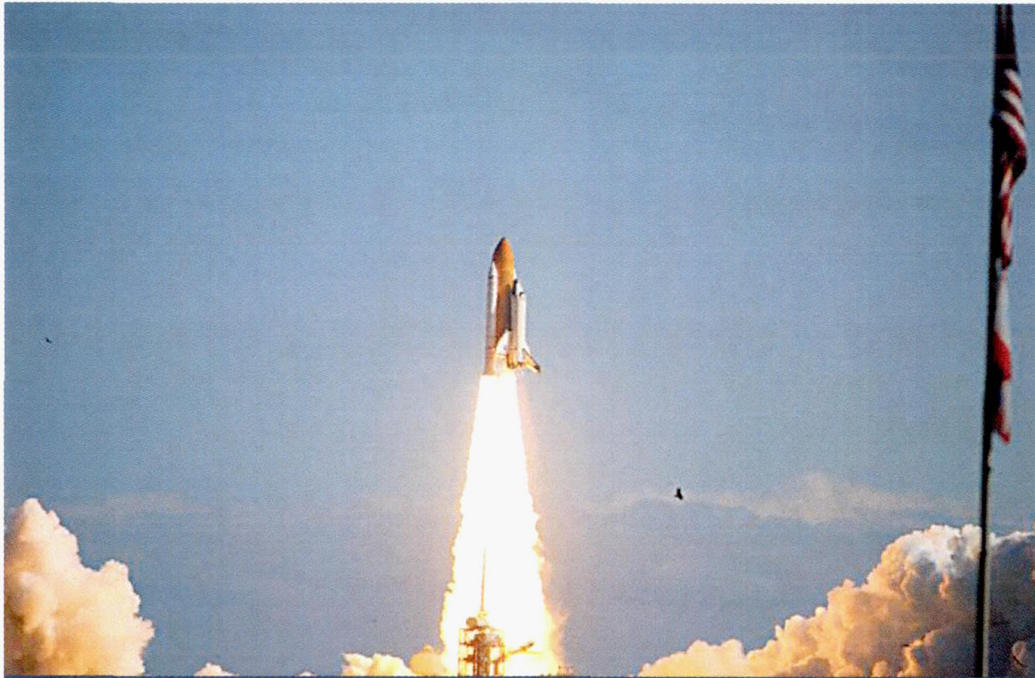




Left Wing  
Leading Edge

STS 107 Rollout and on Launch Pad





STS107 Launch





Shuttle Landing Facility Hangar Prior to Debris Recovery

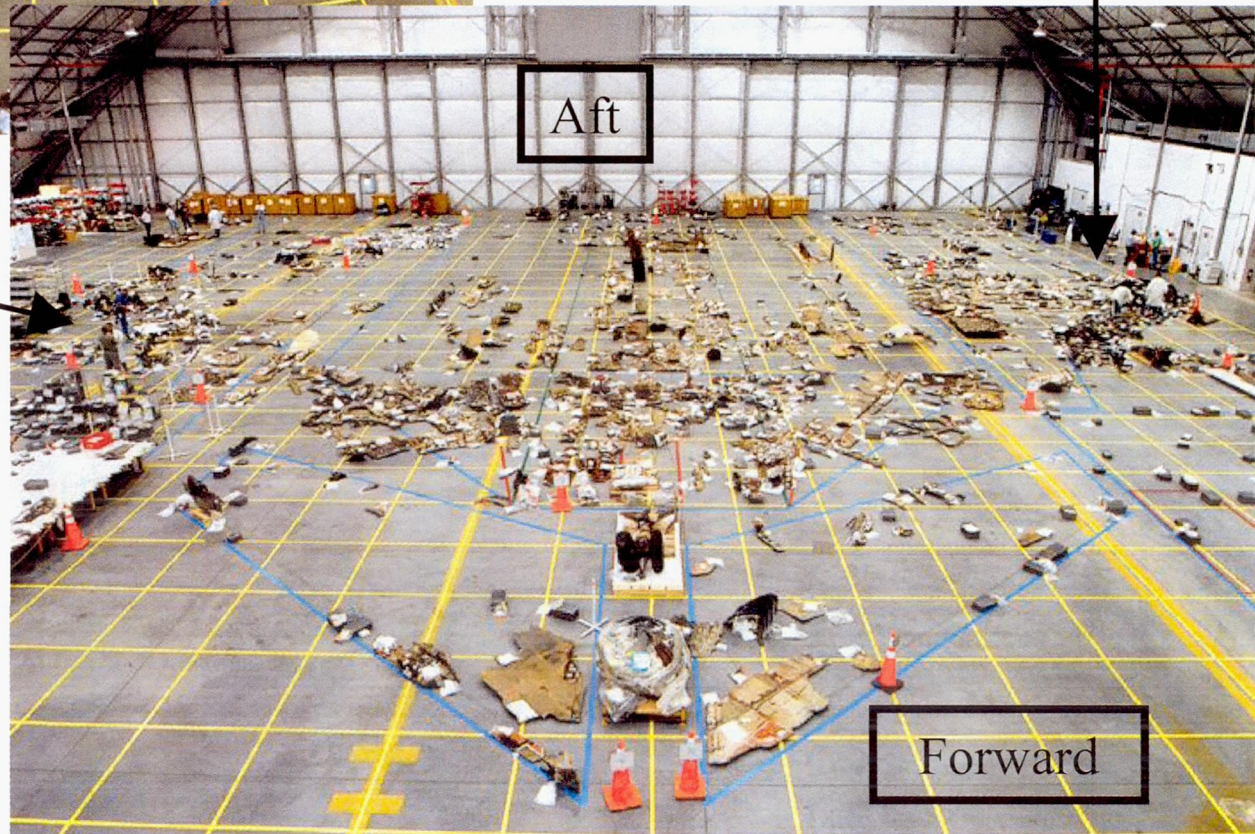




STS107 Reconstruction - Wing  
and Underbelly Surfaces Only

Right Wing

Left Wing



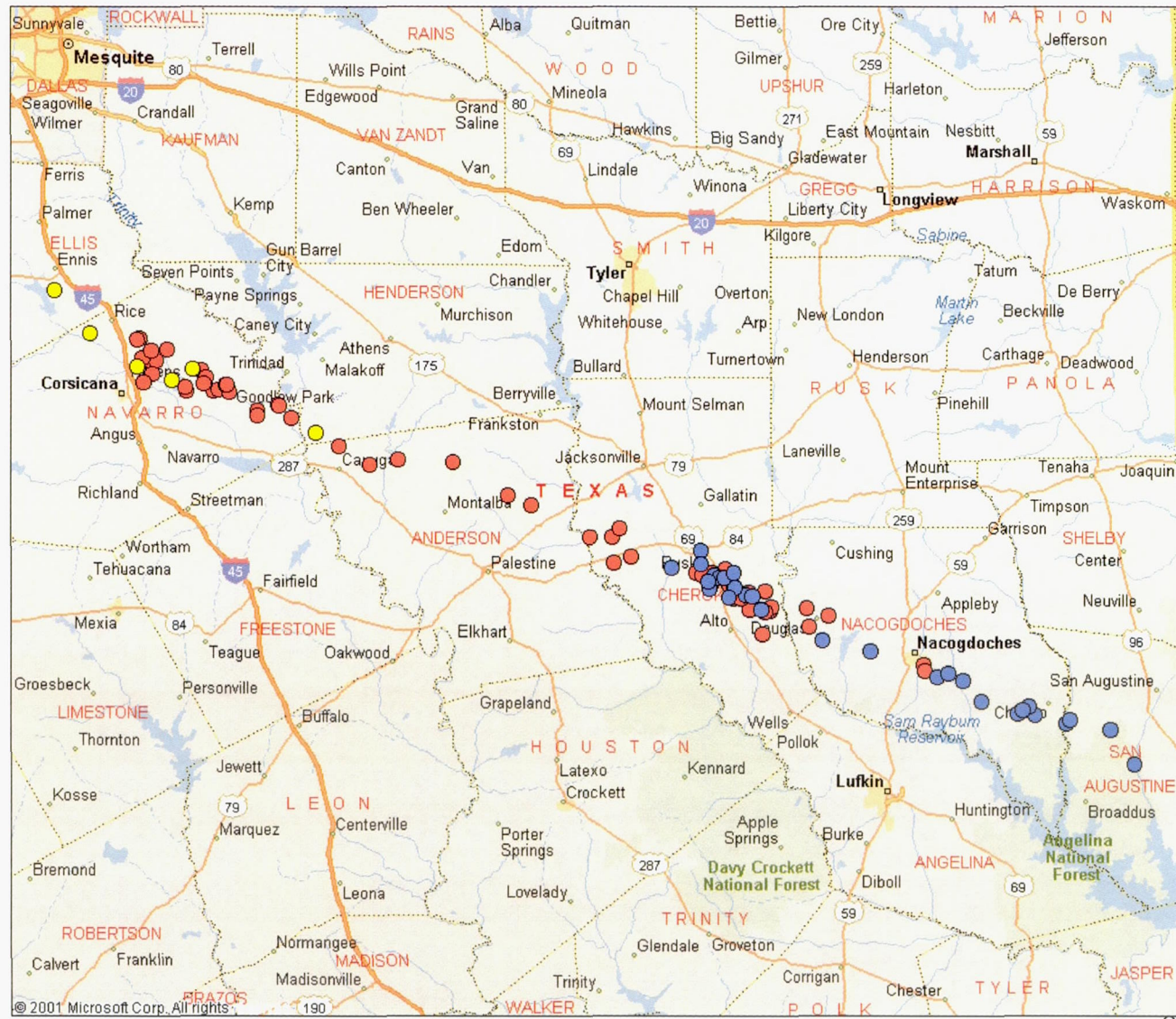
Aft

Forward

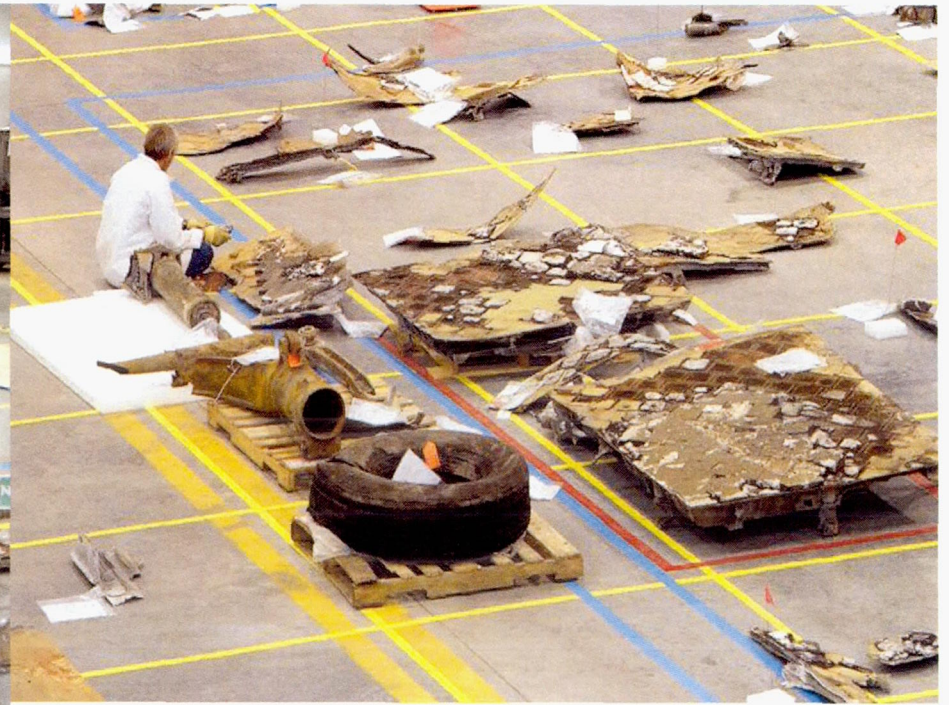


Location of each part found tracked on map - Trend emerges.

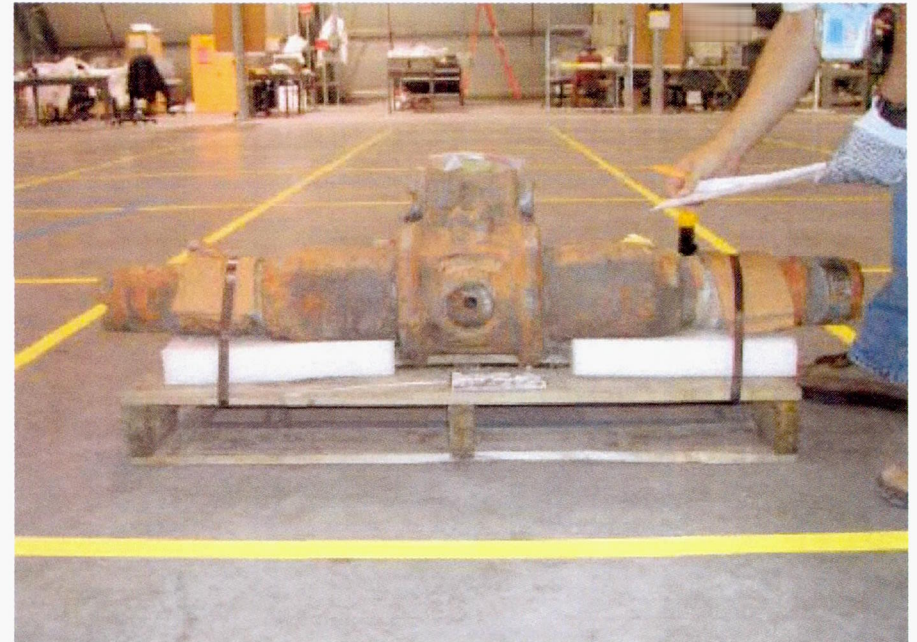
- Left Wing RCC
- Left Wing Eroded RCC
- Right Wing RCC











Believed to be Left Wing Main Landing Gear Assembly





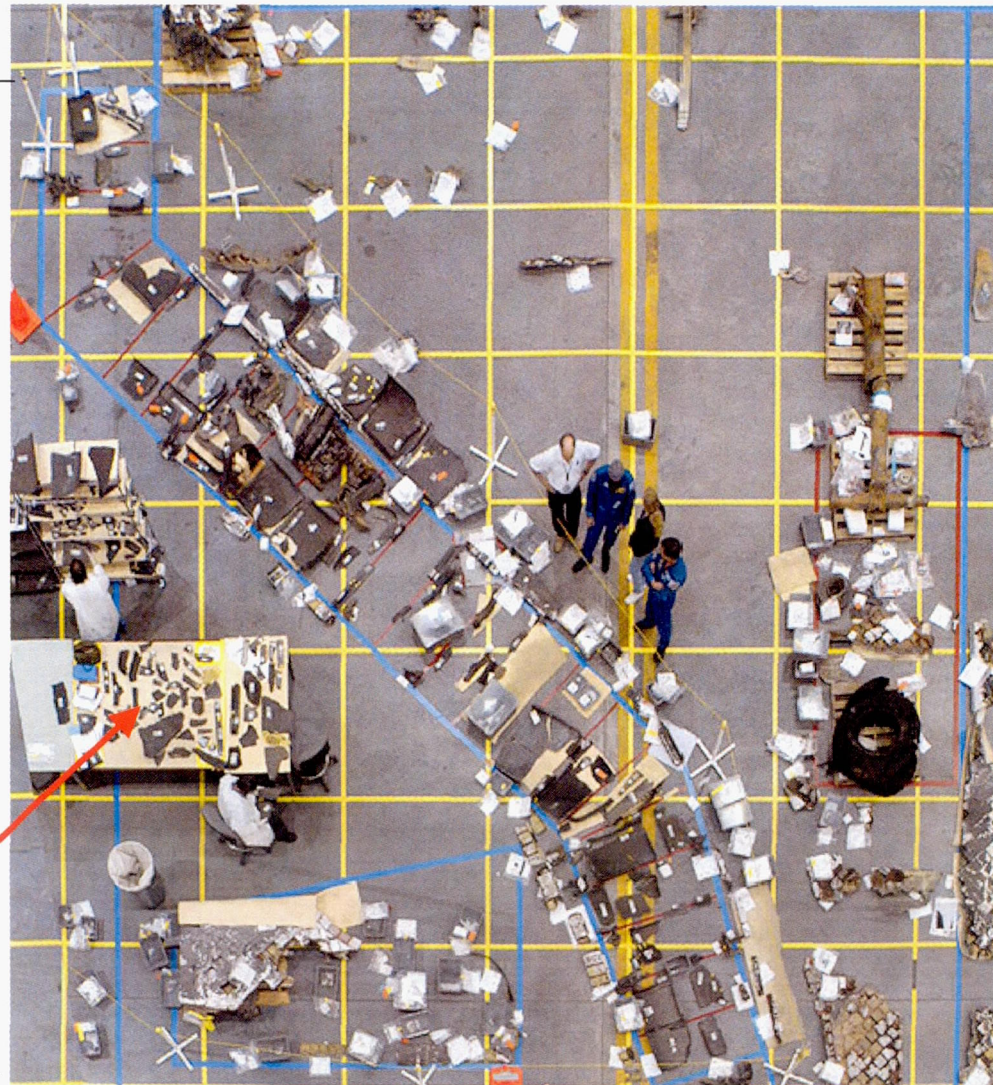


Part Adjacent to Left Main Landing Gear Door



Wing Leading  
Edge RCC  
panels 1-22

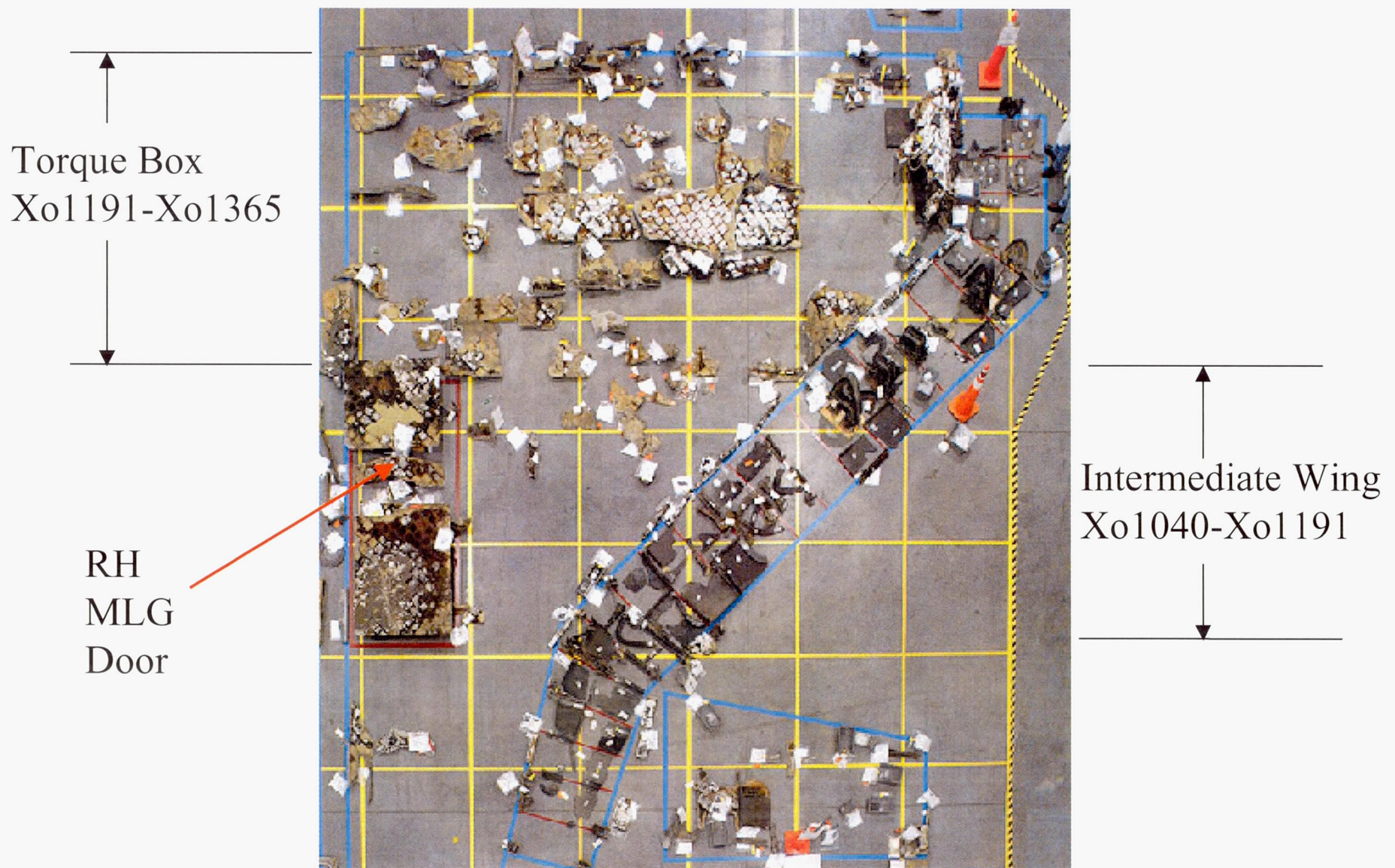
RCC  
staging  
area



Xo1040-Xo1191  
MLG Wheel Well  
Area

Left Wing Leading Edge Recovered Parts – Panels 1-22

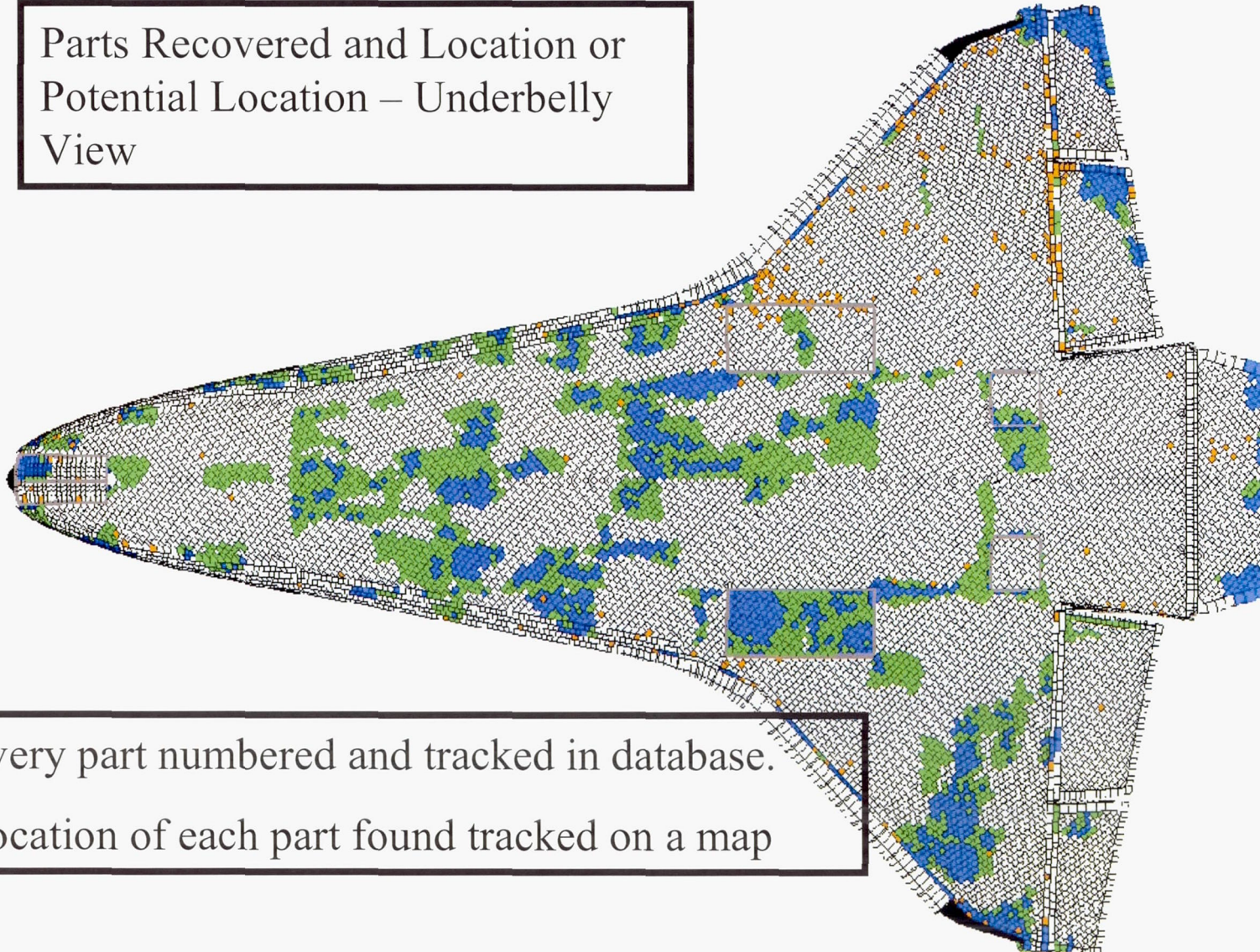




Right Wing Leading Edge Recovered Parts – Panels 1-22



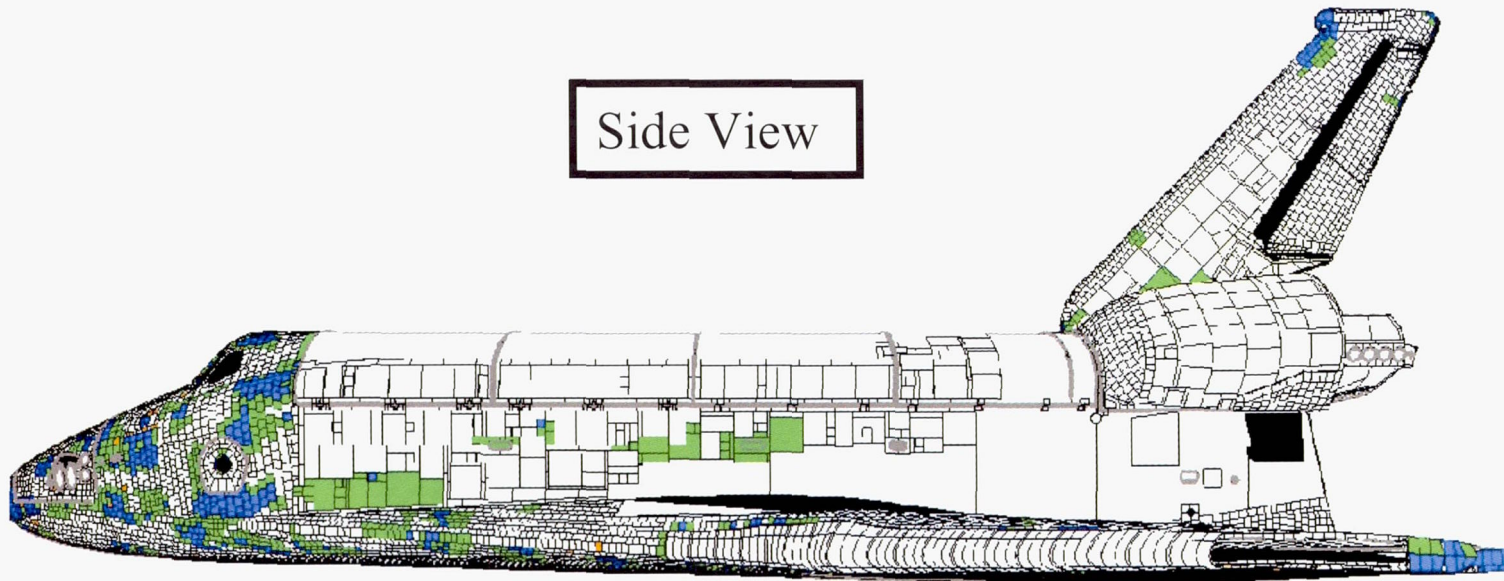
Parts Recovered and Location or  
Potential Location – Underbelly  
View



Every part numbered and tracked in database.  
Location of each part found tracked on a map

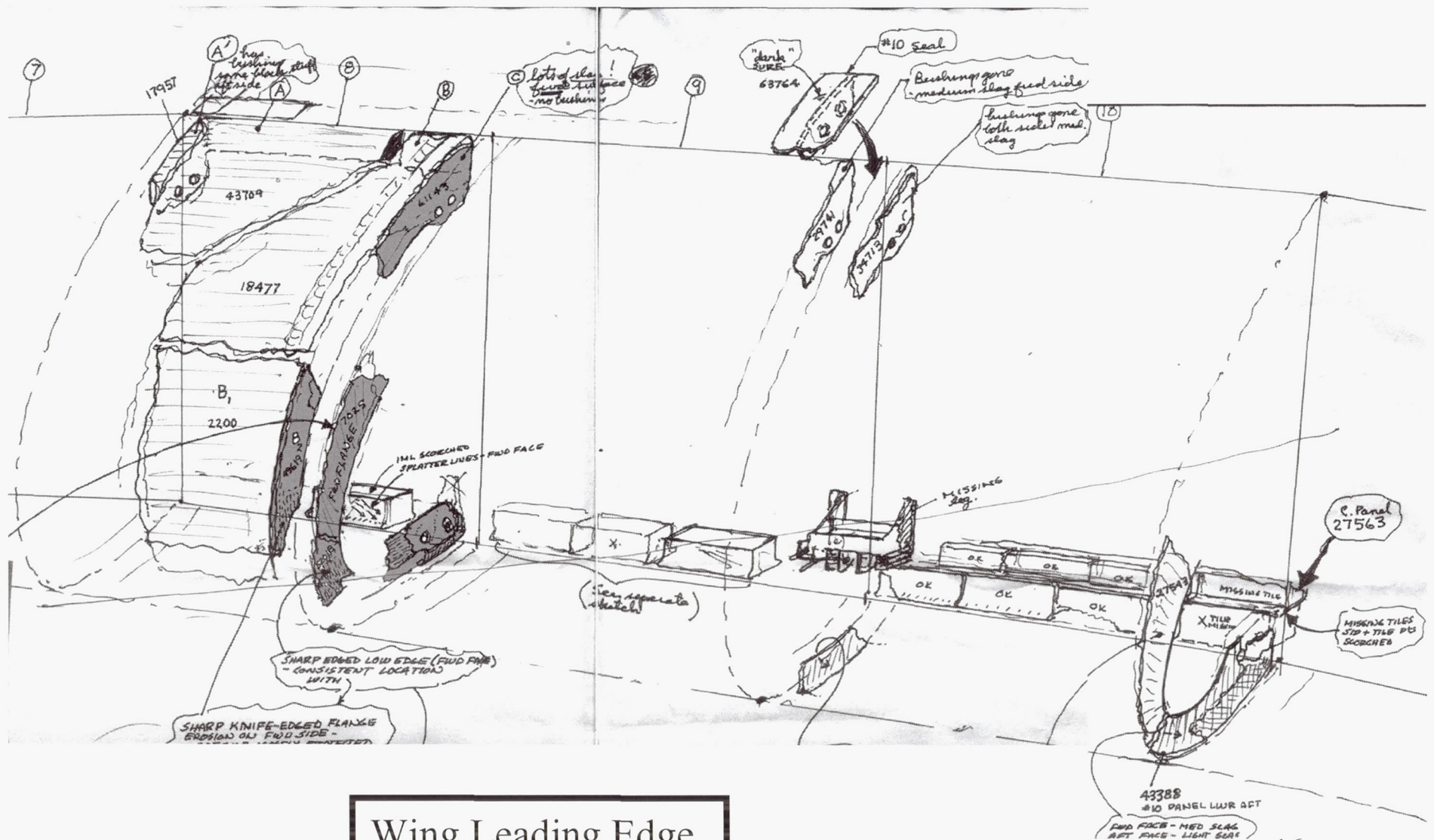


Side View





# Hardware Forensic Team Member Reconstruction Schematic & Notes



Wing Leading Edge





Left Wing Leading Edge  
Final 3D Reconstruction

Left Wing Tile  
Reconstruction

Leading Edge Tiles







STS107 Reconstruction Team



# M&P Organizational Structure

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- Hardware Forensics Team – “Gray Beard” members from Boeing, NASA Langley, NASA Johnson.
  - Evaluate Debris
  - Interact, disseminate and apply findings with other working groups (reconstruction, scenario, fault tree, etc.)
  - Direct specific Failure Analysis. Participate in determining Cause of Failure.
- Materials & Processes Problem Resolution Team.
  - Establish procedures – sample extraction, cleaning...
  - Interface with Hardware Forensics Team.
  - Generate Failure Analysis Plans.
  - Execute Failure Analysis Plans. Provide “Concrete Data”
  - Members included Boeing, USA, NASA KSC, NASA JSC, NASA MSFC, NASA GRC



# When and Where to Begin Failure Analysis?

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- Complex and Challenging Analysis.
- New material added weekly.
- Parts originally located could move as more parts are received.
- Where to Begin? What Questions to ask?
- How many parts to analyze?
- Who to and how to prioritize Failure Analysis?
- How to distinguish between damage in flight vs free fall and impact.
- Initial Constraint – Perform all analysis locally at KSC. Parts could not be sent outside even to other NASA centers.
- CAIB owned the hardware. NASA only in support role.
- Every step/analysis/procedure required documentation through approval from CAIB and NAIT.



# When and Where to Begin Failure Analysis?

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- Breach suspected in Left Wing.
- Begin with Factual Observations (Fact Sheets)
- Let Factual Observations guide the initial analysis.
- Initial Failure analysis included Left Wing:
  - Midbody Panel
  - Main Landing Gear Strut
  - Uplock Rollers
  - Tires
  - Leading Edge Carrier Panel Fasteners
  - Tiles
  - Leading edge RCC material deposit
- M&P Failure Analysis Leads were assigned for each



# Highest Level Questions

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- Where (location in vehicle) did breach(es) occur?
- What specific component(s) failed and how?
- What was the sequence of events?

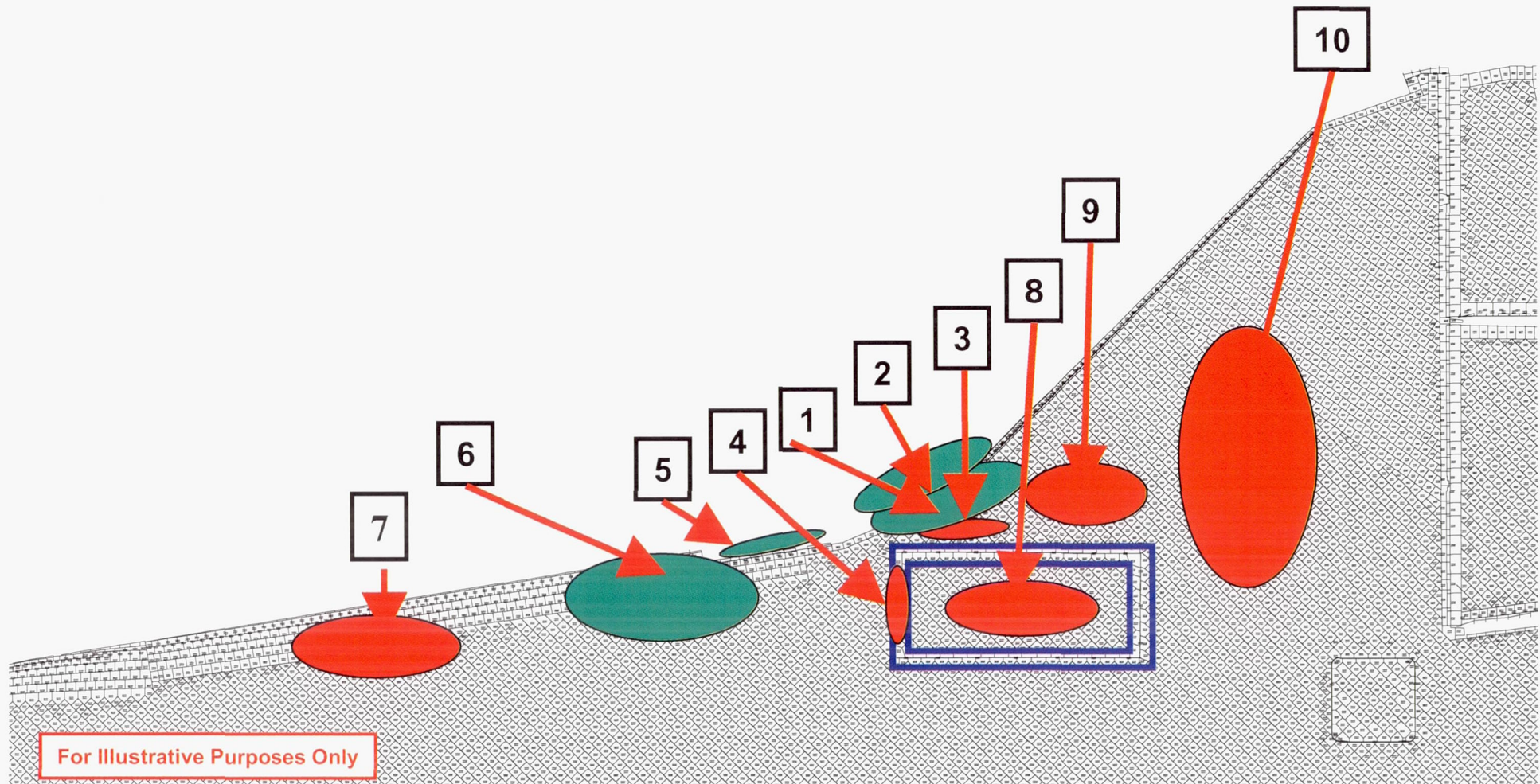


Initial Failure Scenarios and Breach Locations – April 14<sup>th</sup>, 2003

Scenarios Team

Initial Failure Scenarios and Breach Locations – April 14<sup>th</sup>, 2003

Scenarios Team





# Key Finding

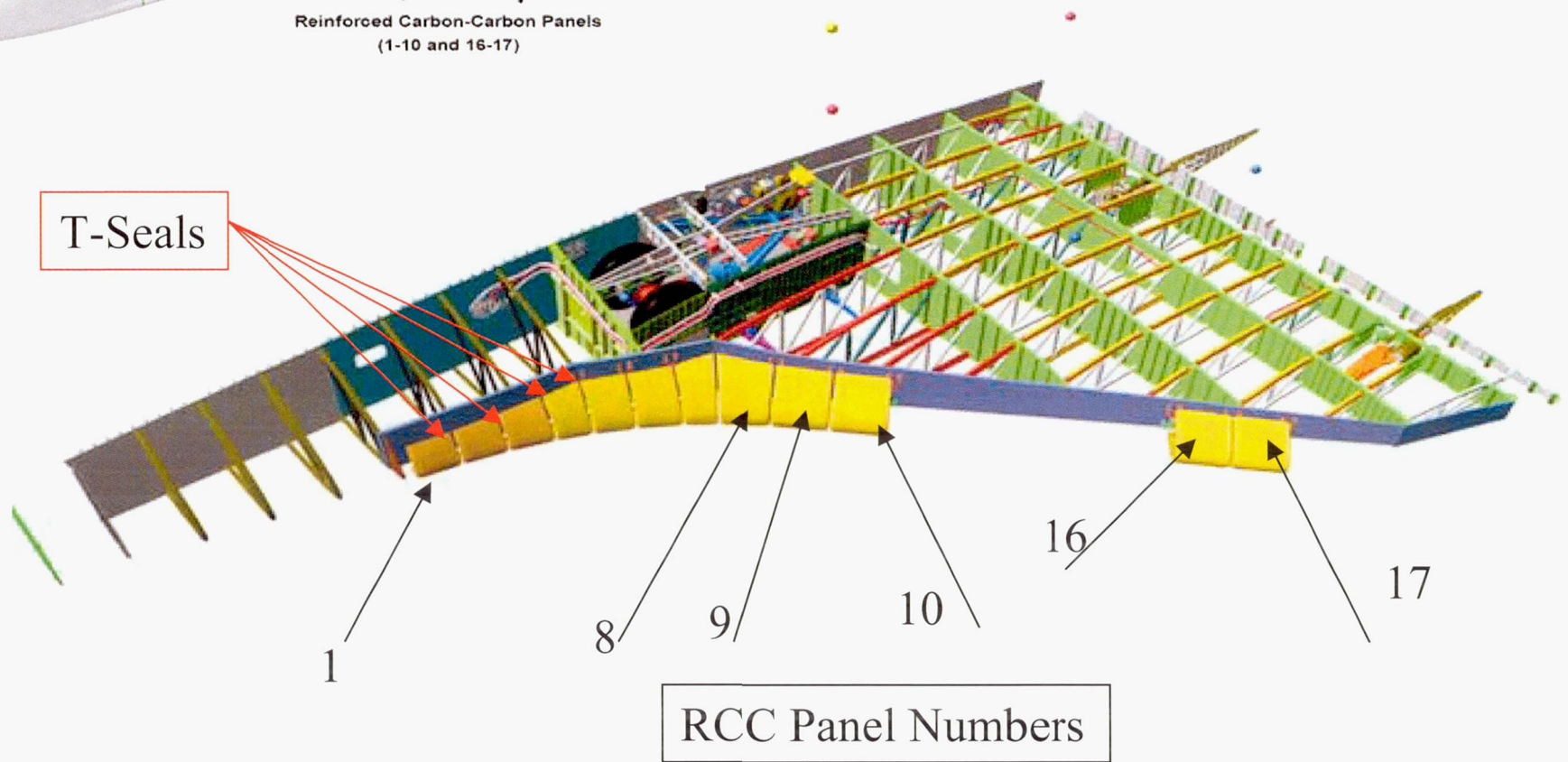
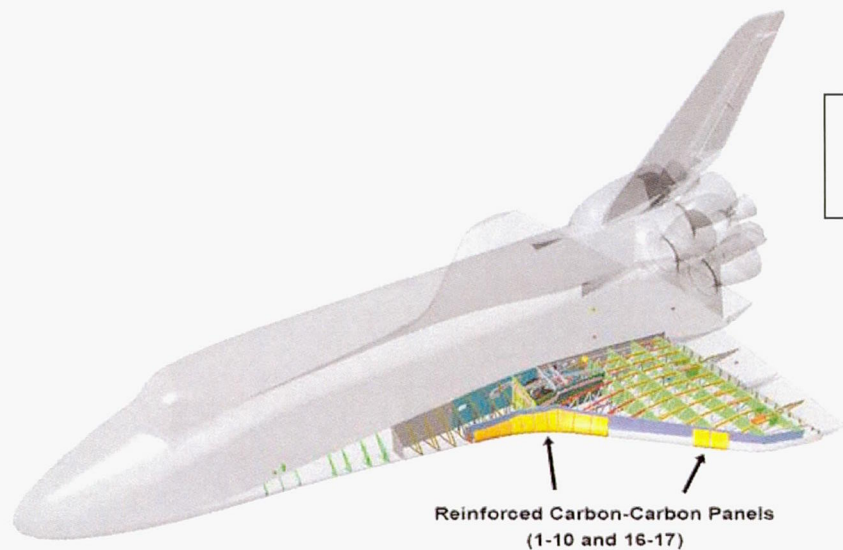
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- MADS/OEX Data Recorder Found–“black box”.
- Key thermocouple inside and outside left wing leading edge panel 9.
- Temperature in this location starts increasing prior to early debris observations.

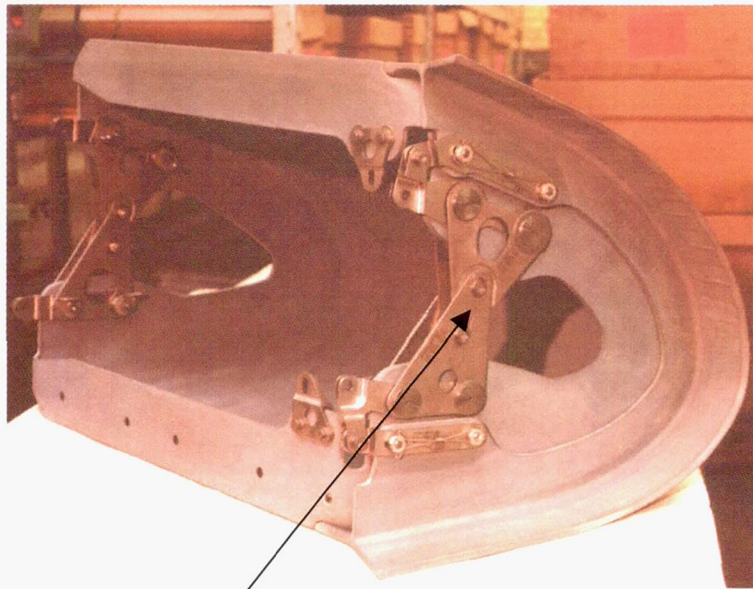
Spotlight/focus shifts to Left wing leading edge damage



# Left Wing Leading Edge

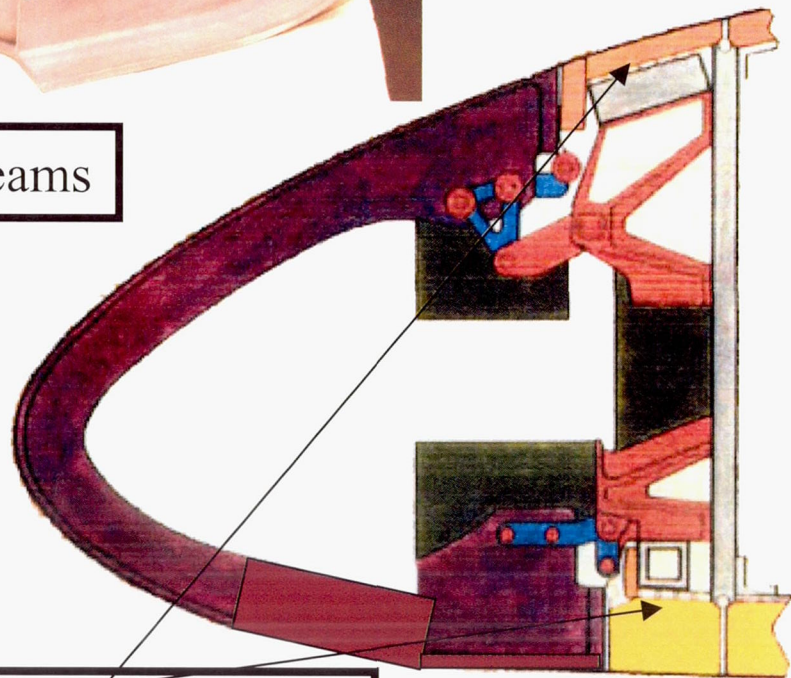






Spanner Beams

Dynaflex insulation – In601 foil with cerachrome fibers inside







Closeout/Carrier Panels and Tiles

RCC panel

RCC rib



- |   |  |
|---|--|
|  RCC      |  Inconel-Dynaflex |
|  Aluminum |  Inconel 718      |
|  LI2200   |  A-286 steel      |
|  LI900    |  |

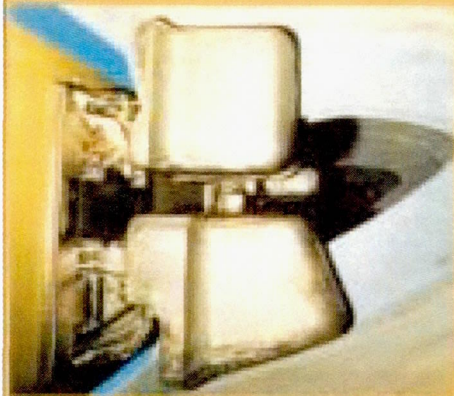




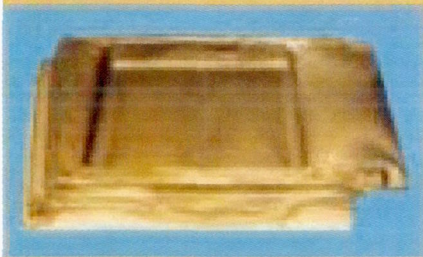
S-82-00703

# Space Shuttle

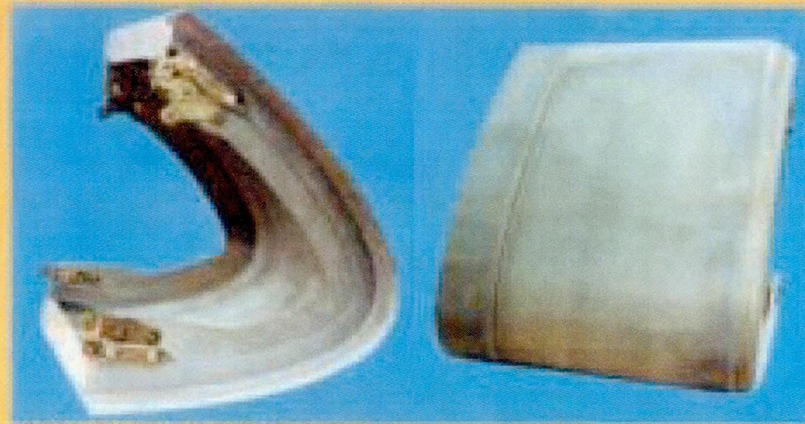
## Wing Leading Edge System



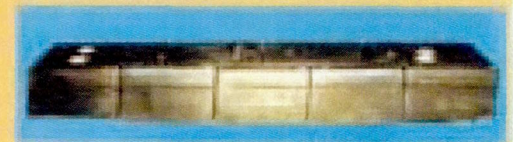
Ear Muff Insulation



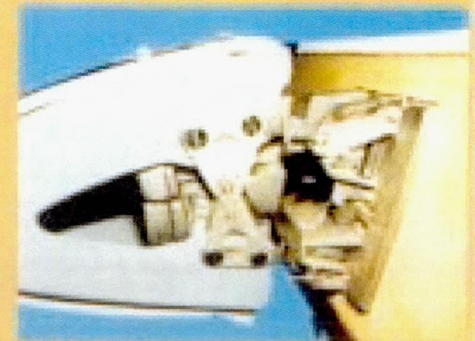
Spar Insulation



RCC Wing Panel



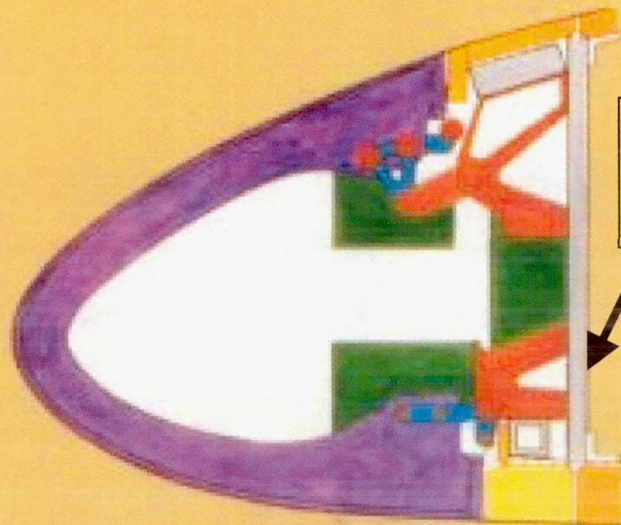
Upper Access Panel



Attachments  
Inconel 718 A-286



Lower Access Panel



Wing  
Spar

LI2200	Inconel 718	RCC	Inconel-Dynaflex
LI900	A-286 steel	Aluminum	



# Left Wing Leading Edge Heat Damage Observations

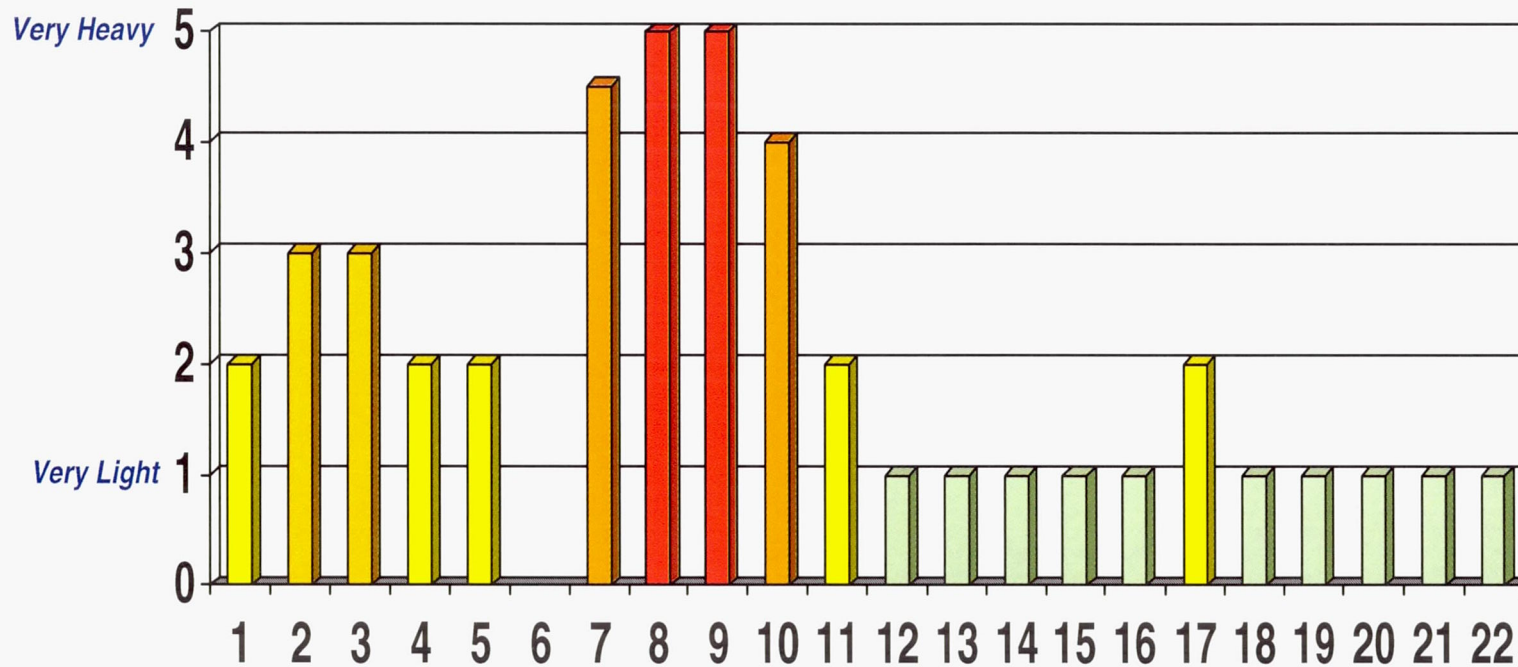
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- Heavy “Slag” deposits on select RCC panels.
- Eroded and knife-edged RCC rib sections.
- Excessive overheating and slumping of carrier panel tiles.
- Missing or molten attachment bolts but intact bushings.
- Deposit mainly on “inside” RCC panel.
- Deposit on some fractured RCC surface.



# Qualitative Deposition Assessment: “Very Light” to “Very Heavy”

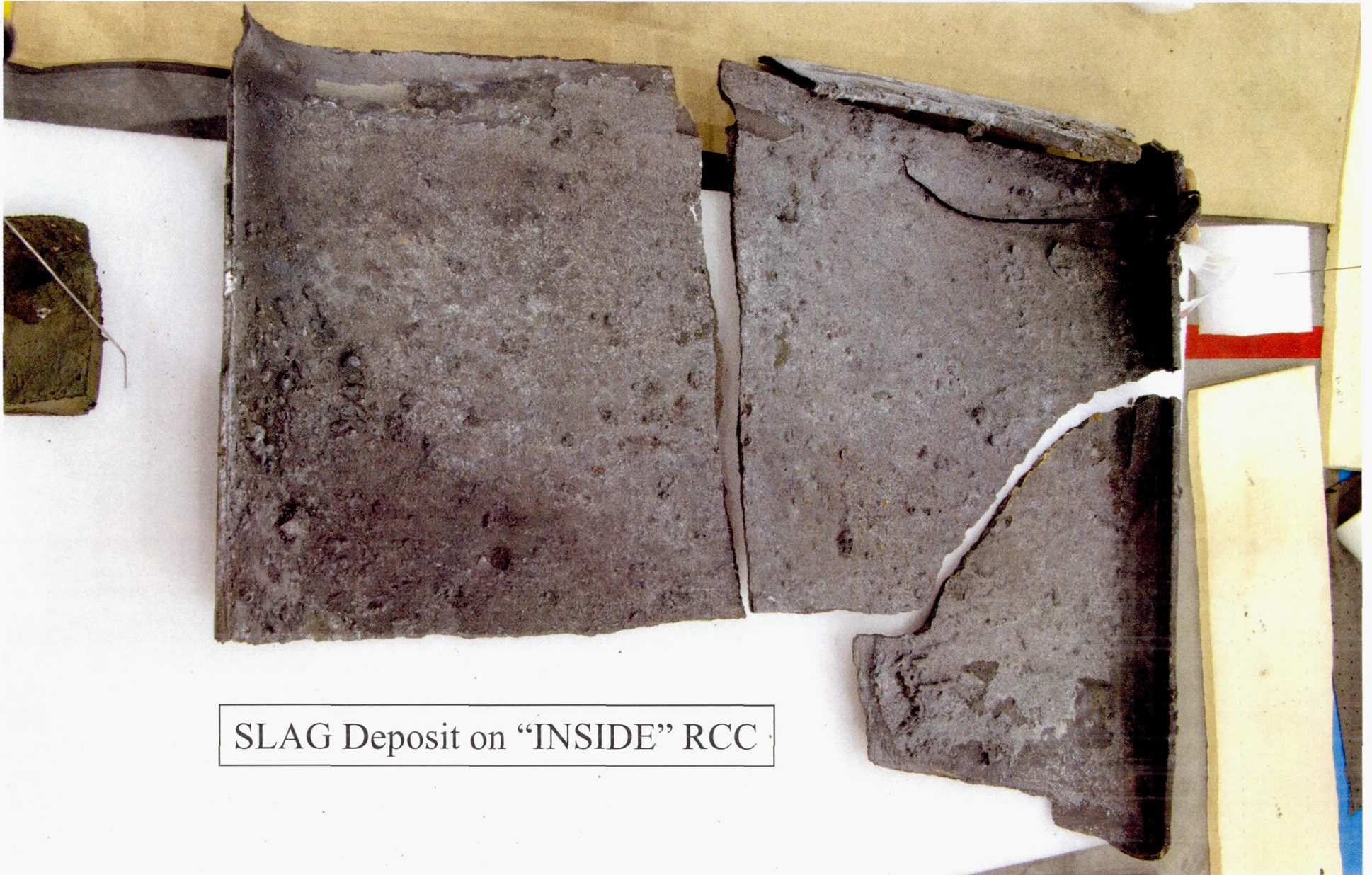
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Distribution of “slag” deposition volume  
was centered around panels 8 & 9 on Left Wing Leading  
Edge RCC.



## Example Debris, LH RCC 8



SLAG Deposit on "INSIDE" RCC



# High Level Questions

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Sample the slag deposits on RCC & Tiles to:

- Identify the location of breach in the wing leading edge.
- Identify the sequence of deposition/events
- Understand plasma flow direction and related thermal damage.



# Analysis Plan Challenges

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- Understand Pros and Cons of Analysis Techniques (destructive and non-destructive)
  - Objective is to downselect analysis techniques fast.
- What are the leading edge materials?
- Understand Chemistry of reactions with atmospheric elements.
- Understand effects of melting and mixing of different materials.
- All analysis to be complete by end of May, 2003.  
Wrap-up in June.



# Analysis Techniques

Analysis Technique	Purpose	Why/Advantages
Photography	Photo documentation	Documentation to maintain traceability
Scanning Electron Microscopy – SEM/EDS	Semi-quantitative elemental composition	Elements present, identify difference between top and bottom of sample
X-ray Diffraction - XRD	Identify compounds	Identify compounds of crystalline structure
Electron Microprobe	Identify elements	Determine exact composition
Fourier Transform Infra-Red - FTIR	Qualitative organic composition	If organic, aid in identification
ESCA/XPS	Identify inorganic & organic compounds	Aid in tracking of oxidation states, such as oxide; compound identification
Metallography + SEM	Layering of material	Composition through deposit layers
Inductively coupled plasma - ICP	Quantitative elemental composition	Elements present, Quantify bulk composition of sample
NDE Inspections- Radiography, CT, Ultrasonics	Non-destructive Inspection and identification	See through the material, identify differences in materials, identify defects

Repeatability and Reproducibility of results emphasized



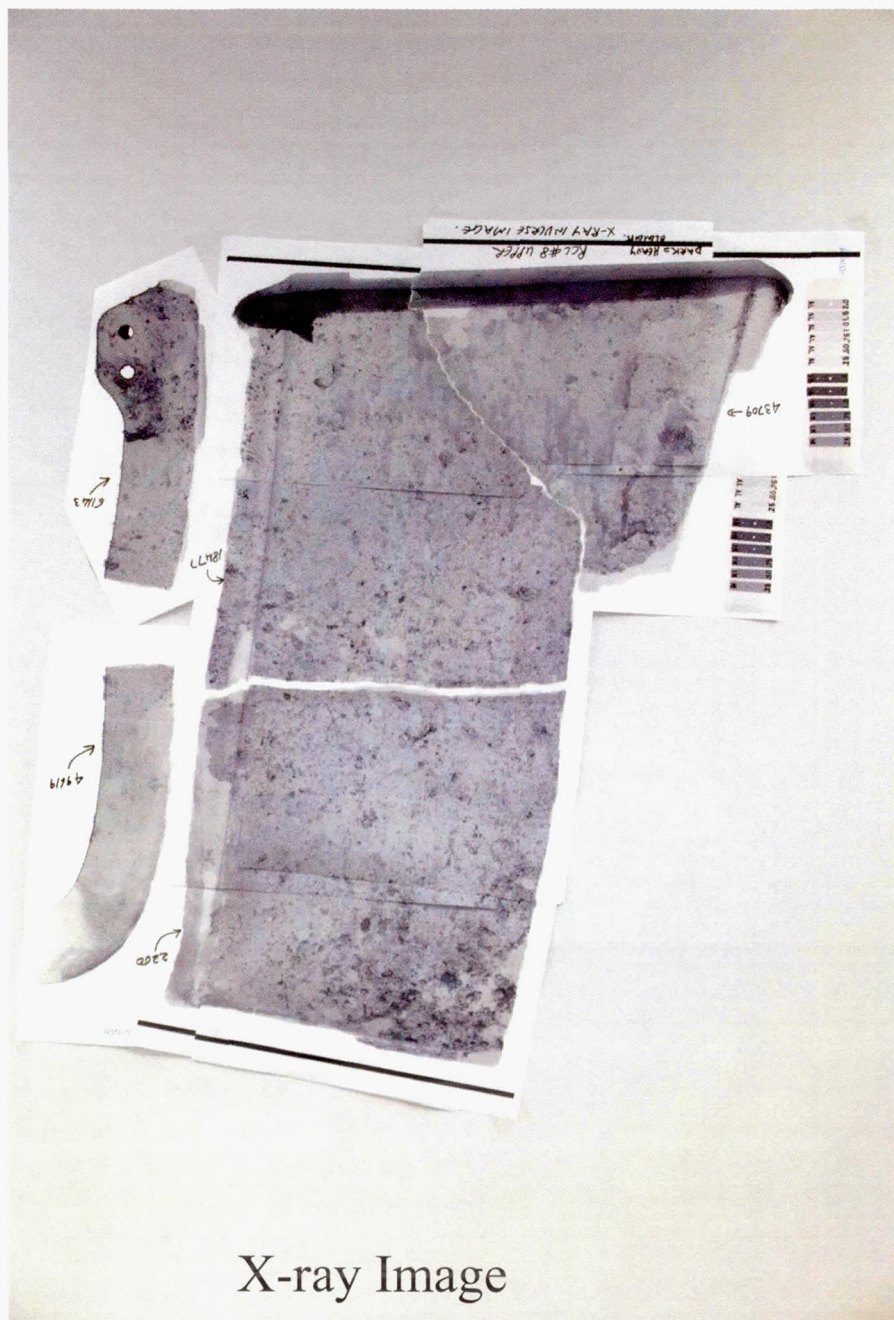
# Approach and Downselection of Analysis Techniques

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- Radiograph RCC panels & Tiles
- Strategically locate samples - minimize the sample count. **Two samples of each feature.**
- Use diagnostic techniques (X-section, SEM, Microprobe, XRD) to identify:
  - Content of slag
  - Layering of slag
- Use “Interpretation Criteria” to correlate deposit analysis  $\Longleftrightarrow$  WLE source material

Apply results to ALL radiographs and visual features to answer the high level questions.





X-ray Image

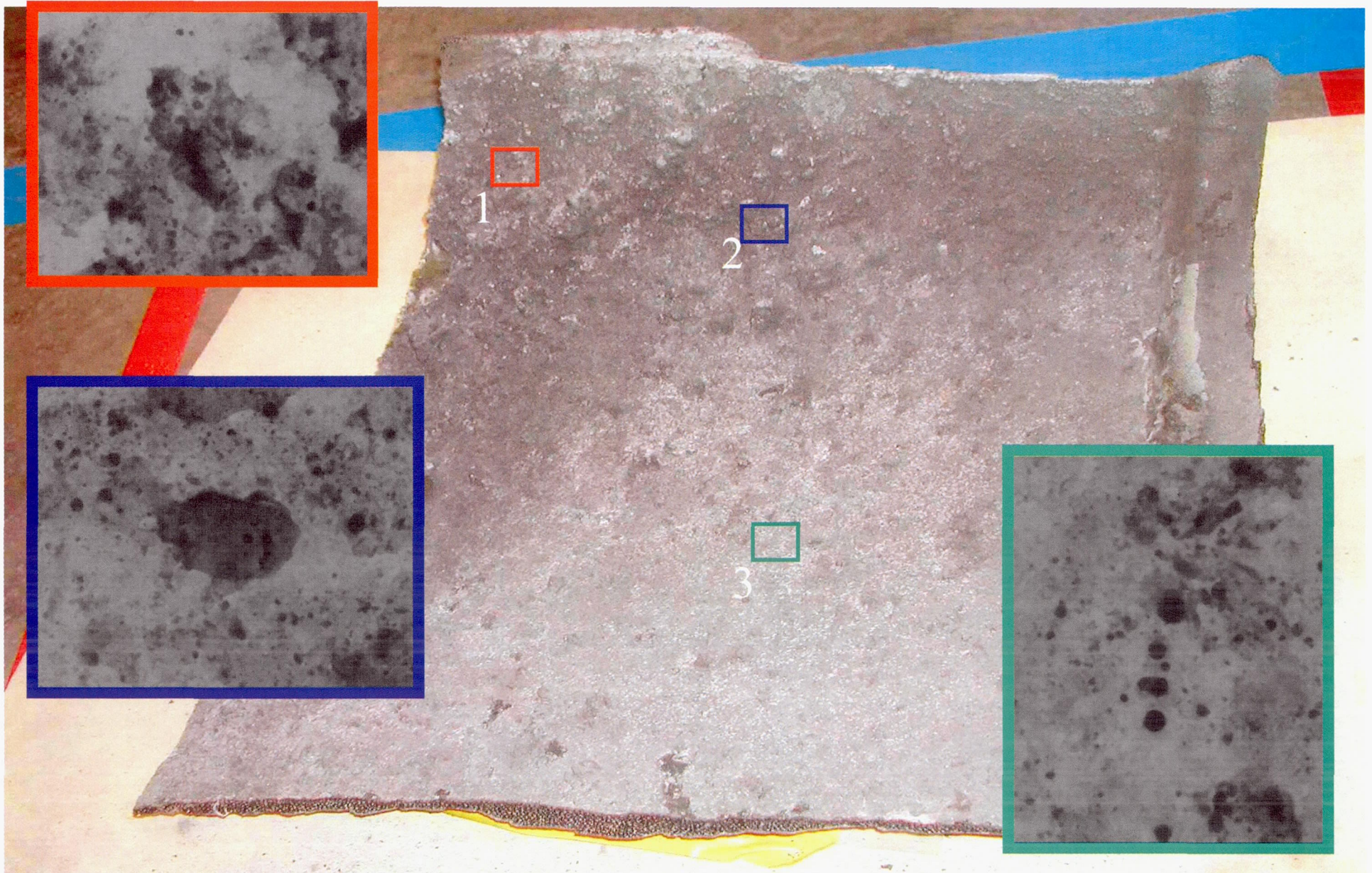


Hardware

Left Wing RCC panel 8. Inside View.



# 2200, LH RCC #8 Upper Apex, Part I, Matches 18477





# Interpretation Criteria - Examples

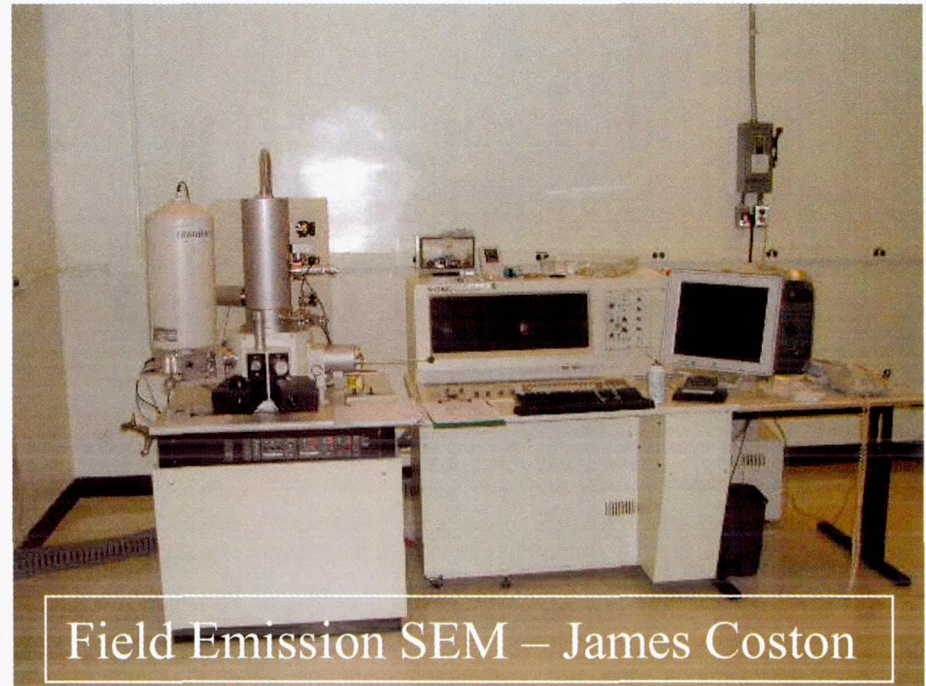
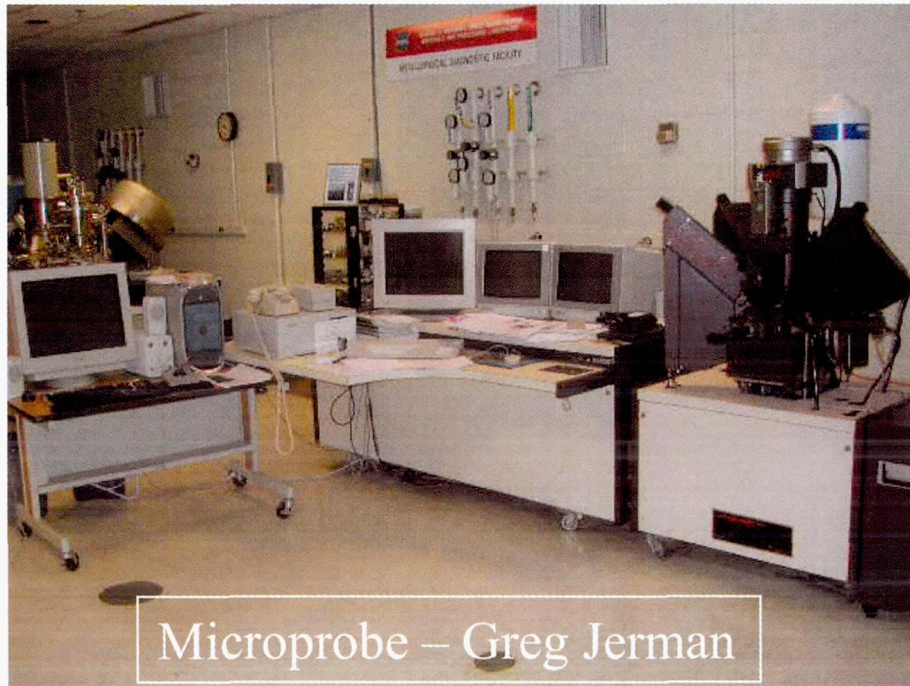
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- **How to identify specific alloys in the deposit?**
  - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
  - 2024 can be identified by presence of metallic Al + Cu,  $\text{Al}_2\text{O}_3$  + Cu.
- **How to identify Cerachrome in deposit?**
  - Cerachrome is approximately 43% $\text{Al}_2\text{O}_3$ 53% $\text{SiO}_2$ 3% $\text{Cr}_2\text{O}_3$ .
  - It can be identified from a combination of back-scattered imaging, color, x-ray diffraction and presence and quantification of Al, Si, O, & Cr.
- **How to identify  $\text{SiO}_2$  from Tile?**
  - $\text{SiO}_2$  from tile will not have with other elements as in cerachrome. It could still pick up a coating of alumina then morphological features will be used to distinguish.



# MSFC Contribution

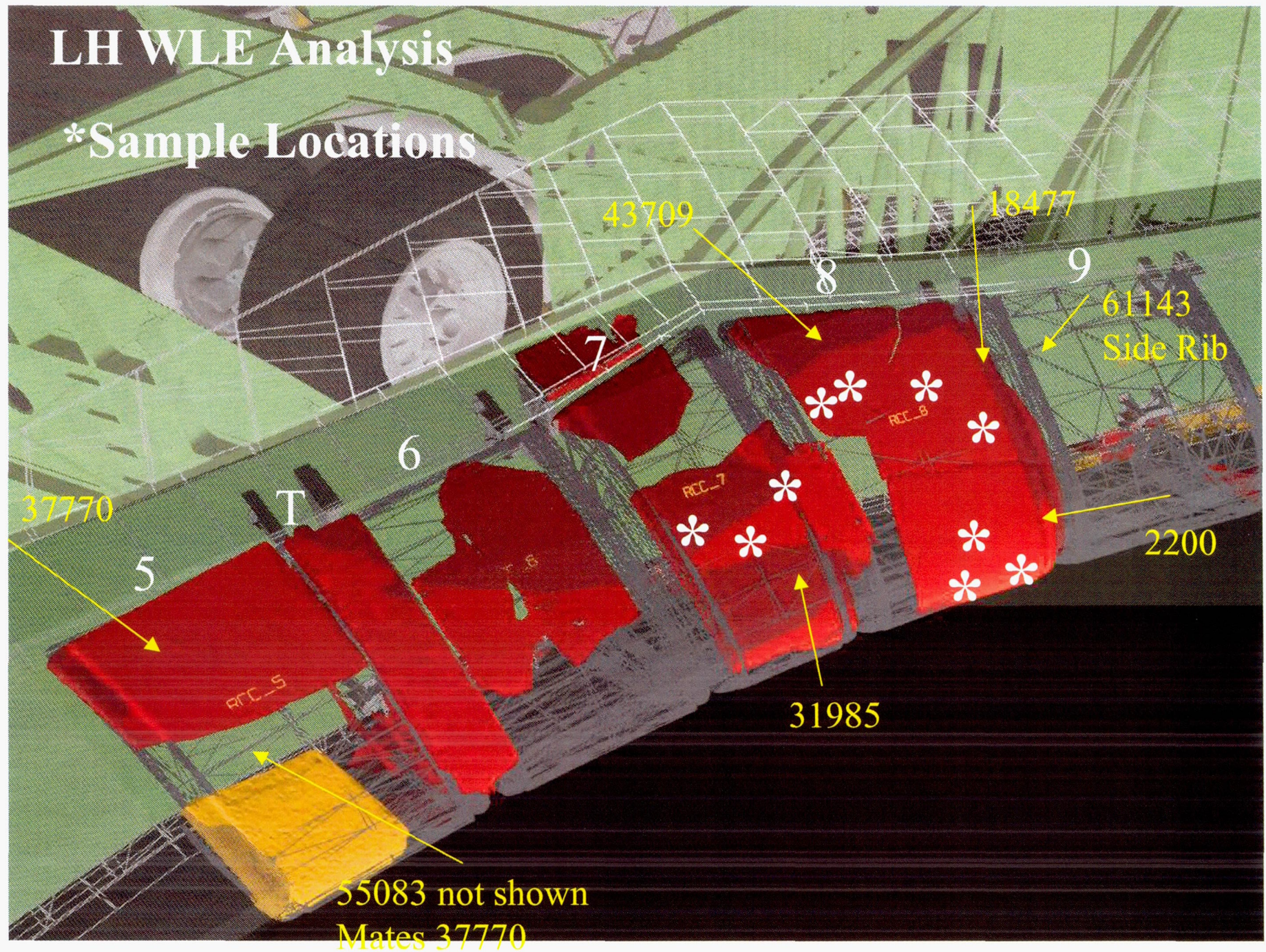
- Help Organize, Plan, and Co-ordinate all sampling activity.
- Metallography, Microprobe, & SEM.
- Generated 1000 pages of data & reports in 6 weeks.





# LH WLE Analysis

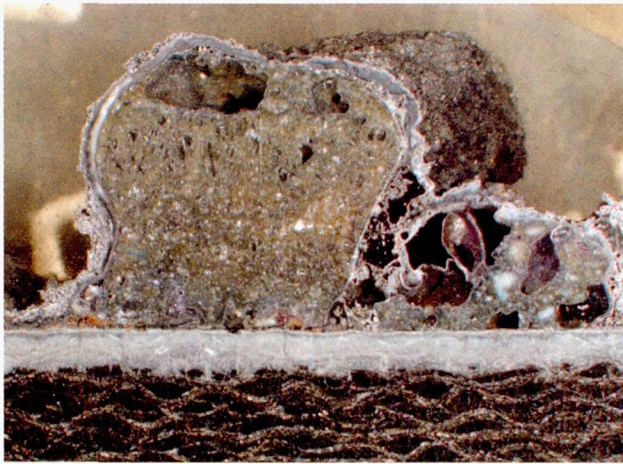
## \*Sample Locations



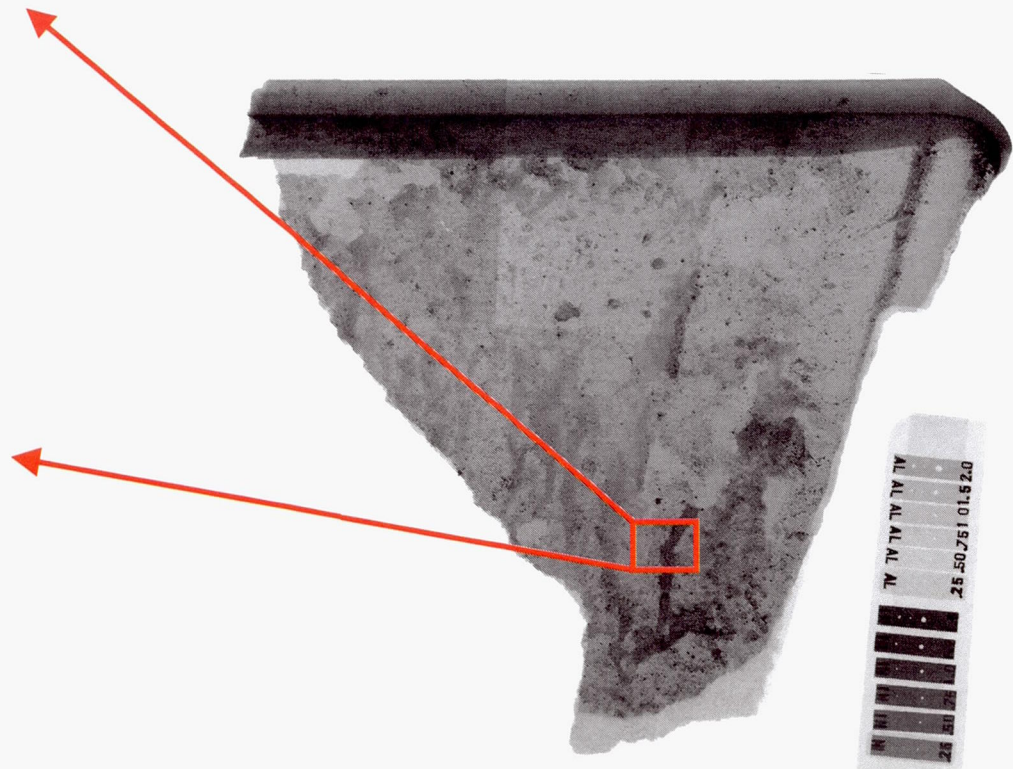


# LH RCC #8 - Slag Feature 1

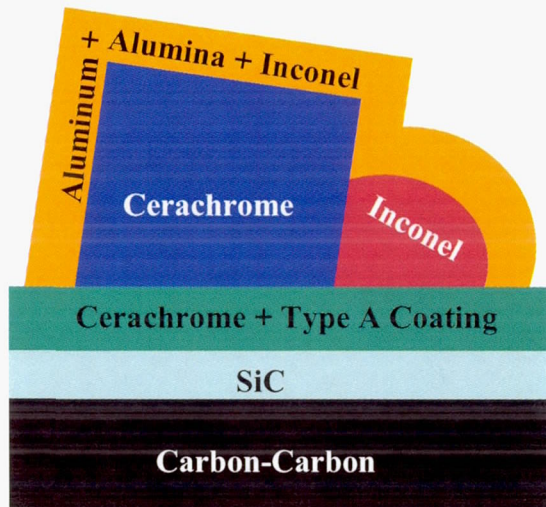
## Thick Tear Shaped



Slag Item 43709, Sample 2A1



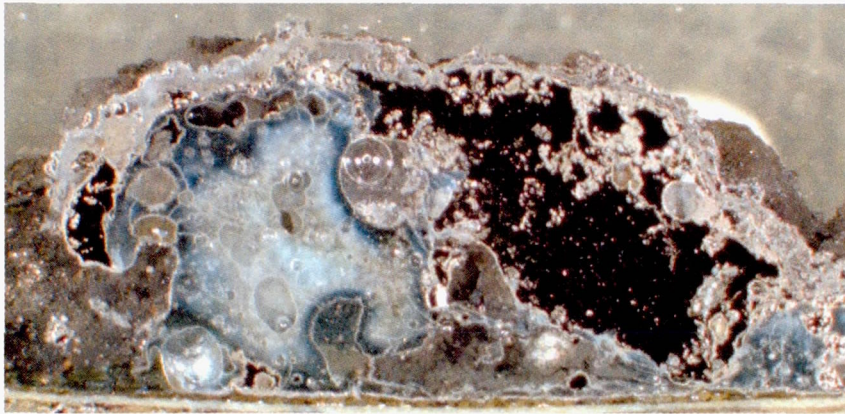
Radiograph of Item 43709



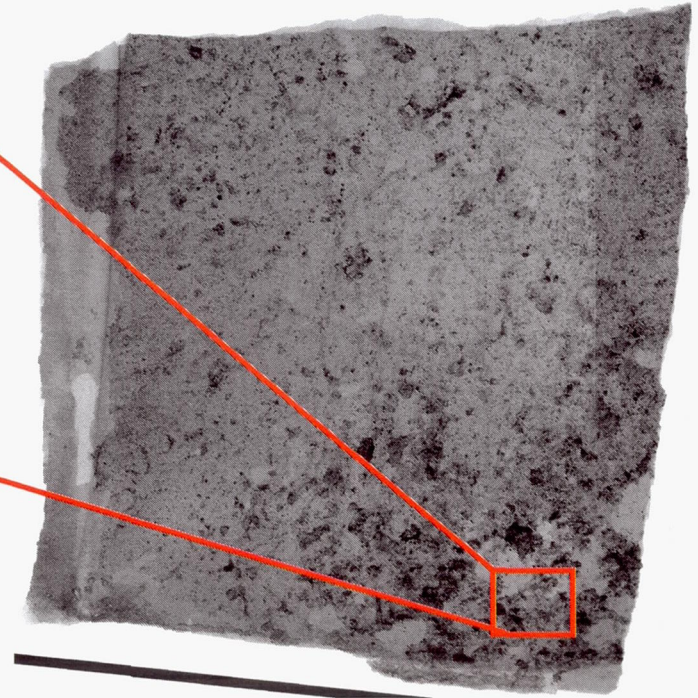


# LH RCC #8 - Slag Feature 2

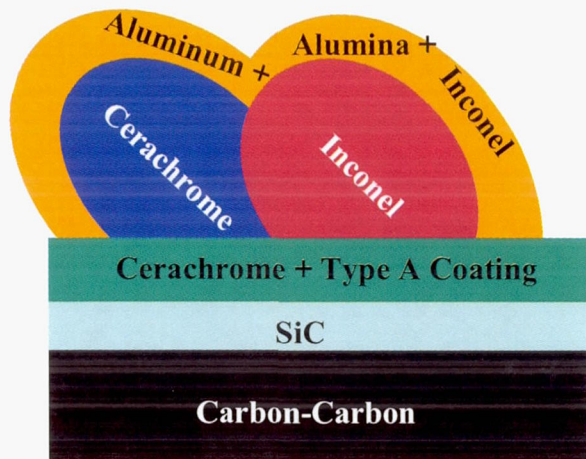
## Thick Globules



Slag Item 2200, Sample 6A1



Radiograph of Item 2200

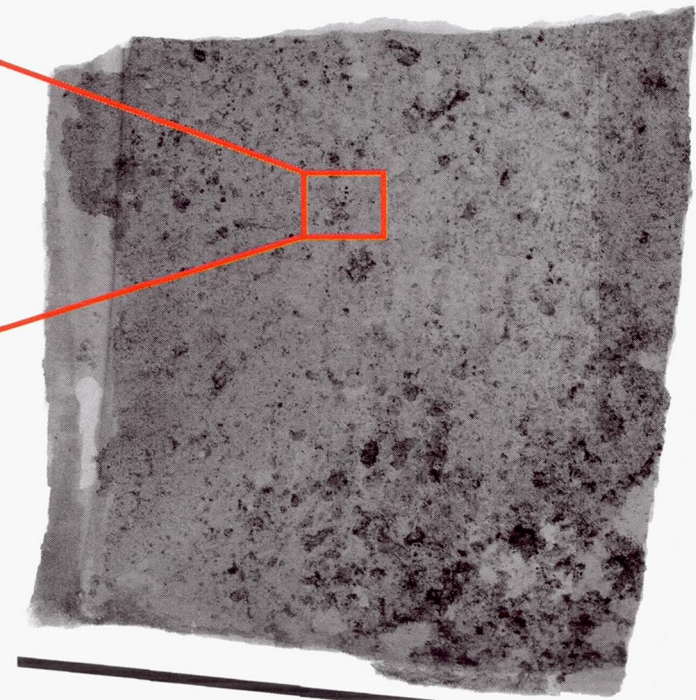
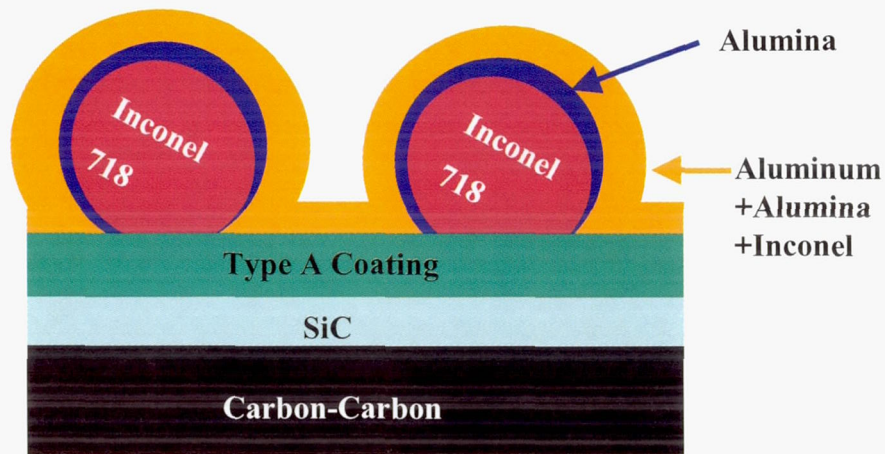




# LH RCC #8 - Slag Feature 3 Spheroids



Slag Item 2200, Sample 6C1



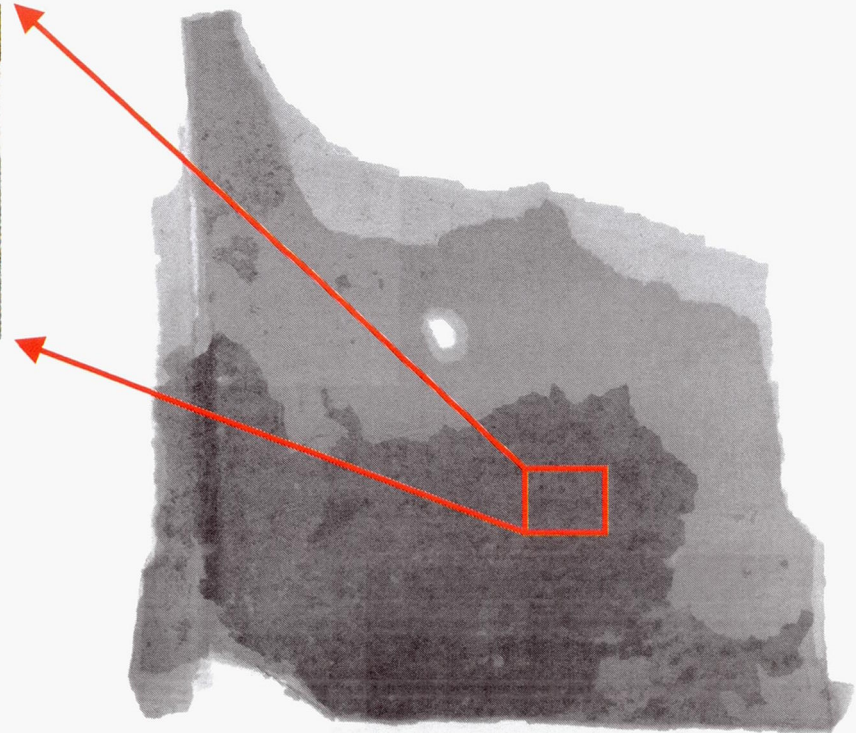
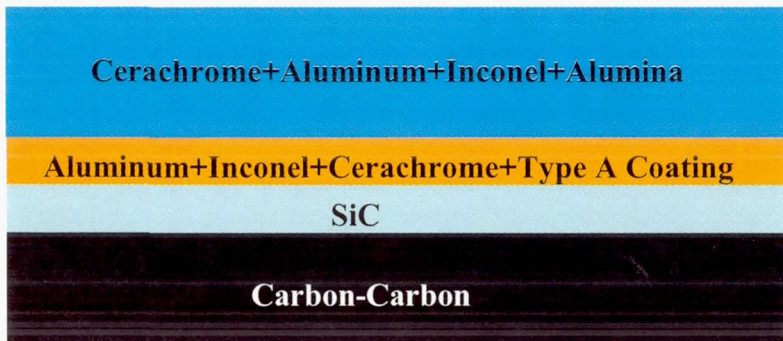
Radiograph of Slag Item 2200



# RH RCC #8 - Slag Feature 4 Uniform Deposit



Slag Item 16523, Sample 4A1



Radiograph of Item 16523



# RCC Slag Significant Findings

## LH RCC #8

- Large amounts of melted ceramic cerachrome insulator
  - High temperature  $>3200^{\circ}\text{F}$
- No indication of stainless steel spar fittings (A286) in slag
  - Breach location away from spar fittings
- Cerachrome + Inconel in first deposited layers
  - Melting of spanner/foil/fittings + Insulator
- Aluminum deposition secondary event

Slag layering suggests plasma impingement location

Slag distribution & shape suggests plasma flow direction and deposition duration



# **RCC Slag Significant Findings**

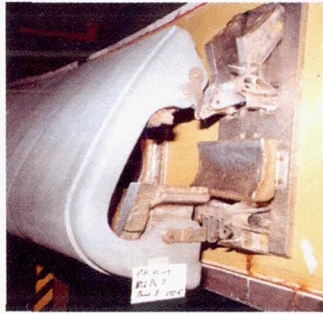
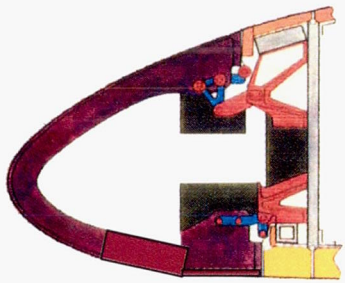
**-All RCC other than LH RCC #8**

**- Including RH RCC panels**

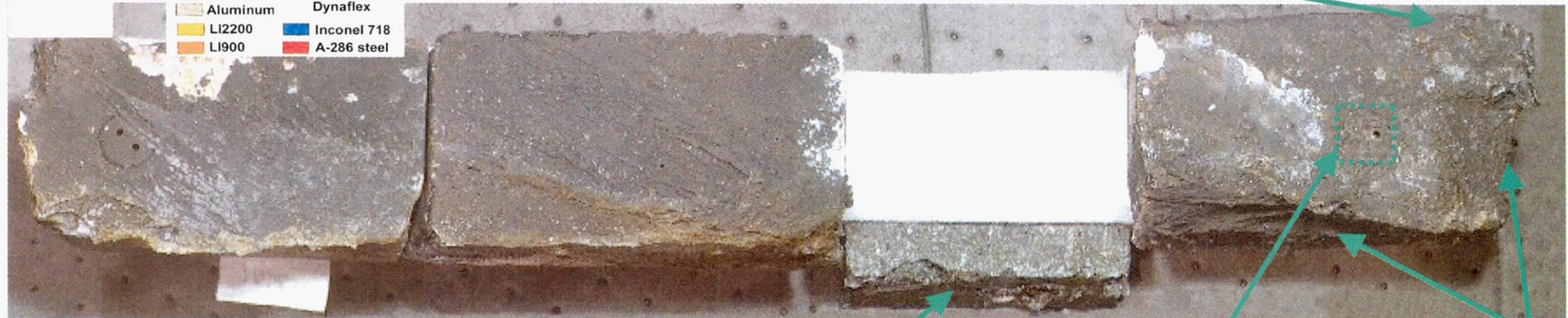
- All analyzed slag layers contain aluminum
  - CONCURRENT Spar/Inconel/Insulator melting
- Slag is generally uniform and relatively thin
  - No region where melting was concentrated i.e. plasma heating for short periods



# Reconstructed View LH CPanel 9 Tiles, lower



■ RCC  
 ■ Aluminum  
 ■ LI2200  
 ■ LI900  
 ■ Inconel-Dynaflex  
 ■ Inconel 718  
 ■ A-286 steel



# 57754

# 22571

# 50338

# 16692

Horse Collar Fabric Deposit

Insert

Tile Slumping

Molten Slag on Tile

C  
P  
8

Spar  
↑  
↓  
RCC

Realtime X-ray, Sidewall View

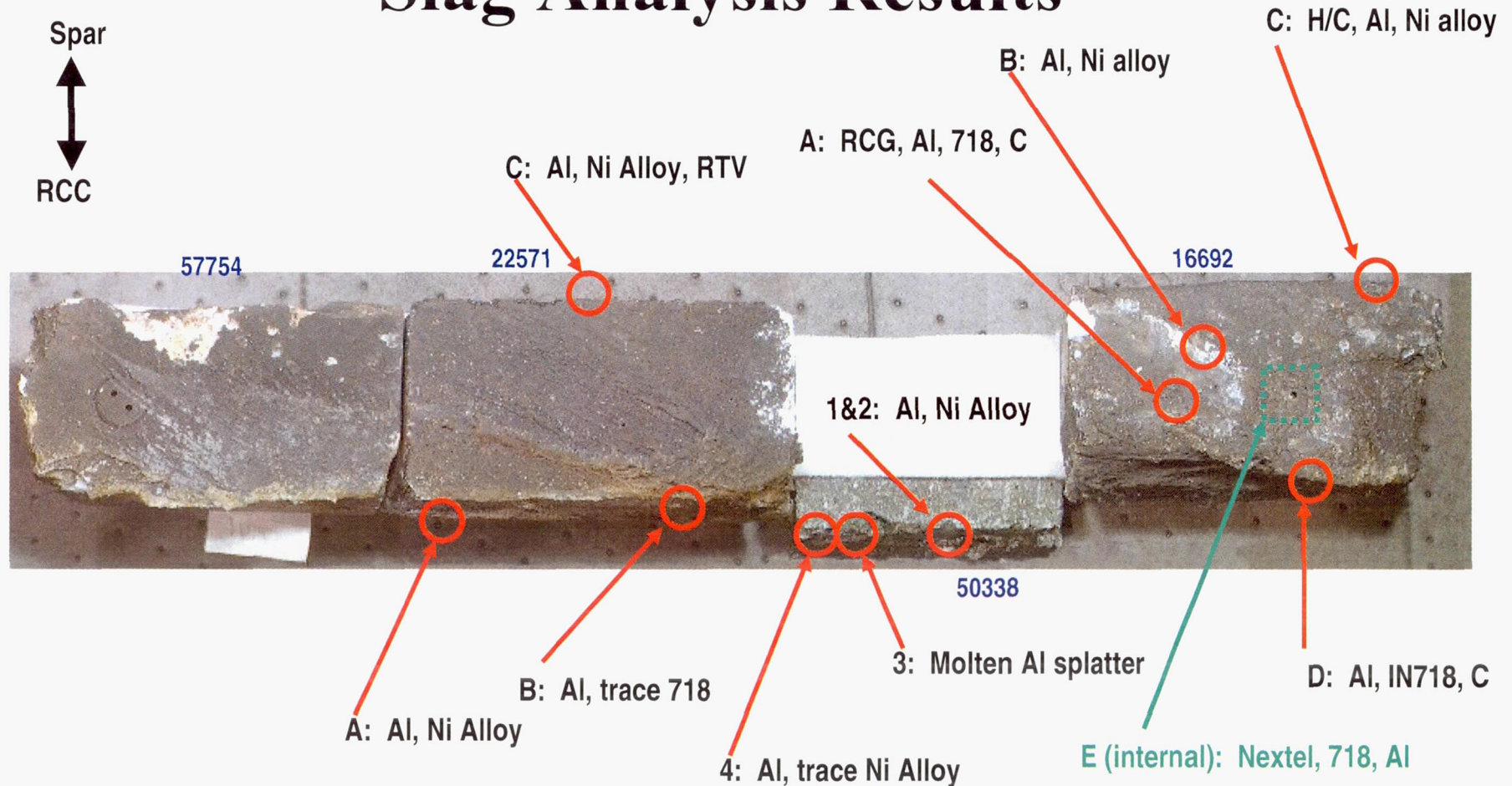
Carrier Panel

High-Z material





# Reconstructed View LH Carrier Panel 9 Tiles, Lower Slag Analysis Results



**These findings suggest flow of material from inside the RCC out through the upper and lower CP locations.**



# Proposed Breach Location & Plasma Flow Based On Slag Results

